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THE HOST GALAXY CLUSTER OF THE SHORT GAMMA-RAY BURST GRB 050509B[1]

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ABSTRACT

The first arcsecond localization of a short gamma-ray burst, GRB 050509B, has enabled detailed studies of a short-burst environment. We here report on studies of the environment of GRB 050509B using the *Swift* X-Ray Telescope (XRT). The XRT error circle of the burst overlaps with an elliptical galaxy in the cluster of galaxies ZwCl 1234.0+02916. Using the measured X-ray flux of the cluster, we estimate that the probability for a chance superposition of GRB 050509B and a cluster at least as X-ray bright as this cluster is $<2 \times 10^{-3}$, presenting the first strong case of a short burst located in a cluster of galaxies. We also consider the case for GRB 050509B being located behind ZwCl 1234.0+02916 and gravitationally lensed. From the velocity dispersion of the elliptical galaxy and the temperature of hot intracluster gas, we model the mass distribution in the elliptical galaxy and the cluster and calculate the gravitational lensing magnification within the XRT error circle. We find that, if GRB 050509B would be positioned significantly behind the cluster, it is most likely magnified by a factor less than 2, but that the burst could be strongly lensed if it is positioned within 2″ of the center of the bright elliptical galaxy. Further mapping of arcsecond-size short-burst error boxes is a new promising route to determine the spatial distribution of old stars throughout the universe.

Subject headings: galaxies: clusters: individual (NSC J123610+285901, Zw 1234.0+2916) — gamma rays: bursts — X-rays: individual (GRB 050509B)

1. INTRODUCTION

About 25% of all gamma-ray bursts detected by the Burst and Transient Source Experiment (BATSE) were "short" (duration less than 2 s; Kouveliotou et al. 1993) and had hard spectra. Due to the nondetection of an afterglow from a short burst, rendering quick and accurate localization unfeasible, their nature has remained elusive. GRB 050509B was detected by the *Swift* Burst Alert Telescope (BAT) on 2005 May 9 at 04:00:19.23 (UT) (Gehrels et al. 2005; Bloom et al. 2005), and upon slewing the *Swift* X-Ray Telescope (XRT) started observations of the burst 62 s after the BAT was triggered. For the first time, an X-ray afterglow from a short burst was detected, enabling a localization within 9″.3 (Gehrels et al. 2005). Imaging of the XRT error box showed that it overlapped with an elliptical galaxy with a redshift of $z = 0.2248$ (Bloom et al. 2005). Based on the unlikeliness of a chance alignment between GRB 050509B and such a galaxy, it has been argued that this is the host galaxy of the burst (Bloom et al. 2005; Gehrels et al. 2005). However, several much fainter (and presumably more distant) galaxies were also detected within the XRT error circle (see Fig. 1 in Hjorth et al. 2005). A unique feature of GRB 050509B is that it is situated in the direction of a nearby cluster of galaxies, identified in the Zwicky catalog (ZwCl 1234.0+02916; Zwicky & Herzog 1963) and in the Northern Sky Optical Cluster Survey with a photometric redshift of $z = 0.2214$ (NSC J123610+285901; Gal et al. 2003). X-ray emission from a hot intracluster medium in ZwCl 1234.0+02916 is clearly detected by the XRT from which Bloom et al. (2005) determined the cluster X-ray centroid and temperature. If GRB 050509B is hosted by one of the fainter galaxies beyond the cluster, the emission from the burst is inevitably boosted by gravitational lensing. This could enhance the probability of detecting the burst and imply a (possibly large) correction to the derived burst energetics.

Here we (1) derive the X-ray flux, temperature, and mass of the cluster ZwCl 1234.0+02916 and estimate the probability of a chance alignment of a gamma-ray burst and a cluster with an X-ray flux at least as large as that of ZwCl 1234.0+02916, and (2) calculate the gravitational lensing magnification within the GRB 050509B XRT error circle, constraining scenarios where GRB 050509B is gravitationally lensed. A cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ is assumed throughout this Letter. All errors quoted are 90% confidence limits.

2. OBSERVATIONS AND DATA REDUCTION

The *Swift* XRT (Gehrels et al. 2004) observed the GRB 050509B region for a duration of 75 ks. The X-ray afterglow of GRB 050509B is detected during the first 400 s of the XRT observation. We investigated the X-ray emission from an intracluster medium in the cluster ZwCl 1234.0+02916, by analyzing XRT data obtained after the first 400 s where the GRB 050509B X-ray afterglow had faded below detection. Only data taken in "photon counting mode," providing full imaging and spectroscopic information, were included in the analysis, yielding 31.9 ks of exposure time. Using the `xrtpipeline` procedure version 0.8.8 in the HEAsoft 6.0 software package,[6] we applied standard screening parameters and the latest available calibration files (2005 June 1) to the level 1 data obtained from the *Swift* Quick-Look Data compilation[7] to produce cleaned event lists of the full XRT field of view. Subsequently, the

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[6] See http://heasarc.gsfc.nasa.gov/docs/software/lheasoft.

[7] See http://swift.gsfc.nasa.gov/cgi-bin/sdc/ql?, data sequence 00118749000.

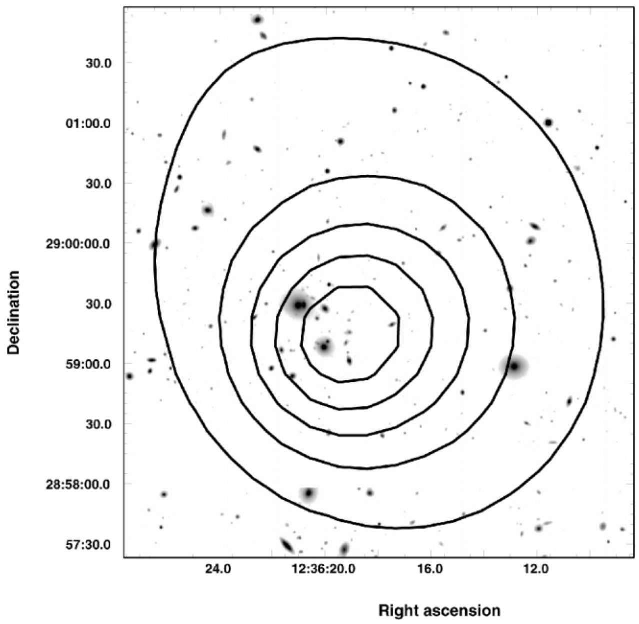

FIG. 1.—X-ray contours from an adaptively smoothed XRT 0.3–10 keV image with point sources removed, overlaid on a VLT FORS2 *R*-band image of ZwCl 1234.0+02916 (Hjorth et al. 2005). The outermost contour (7.0×10^{-6} counts arcsec^{-2} s^{-1}) corresponds to 1.5 times the background, and the contours increase consecutively by a factor of 1.5. The region between declinations +28°57′58″ and +28°58′20″ is not covered due the FORS2 chip gap.

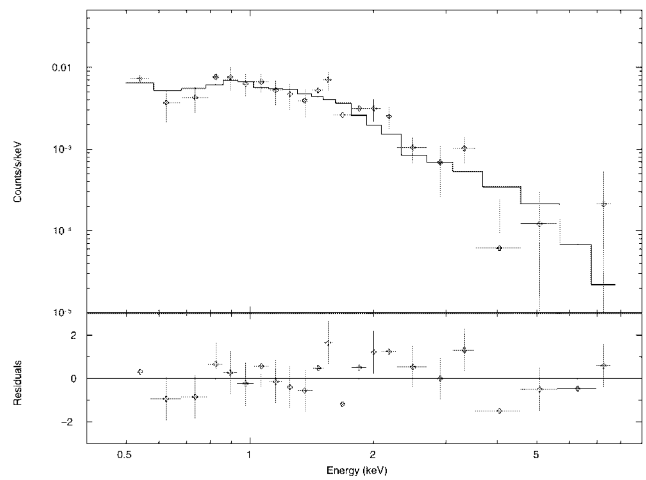

FIG. 2.—*Top panel*: XRT X-ray spectrum of the cluster emission with the best-fit absorbed MEKAL hot plasma model. *Bottom panel*: Residuals from the best fit in units of standard deviations.

`xselect` tool in the HEAsoft 6.0 package was used to produce images and spectra with the spatial and spectral filters given below.

An image was obtained in the 0.3–10 keV band, and sources were detected using a wavelet algorithm (`wavdetect` implemented in the Chandra Interactive Analysis of Observations [CIAO][8] ver. 3.2 software package). The astrometry was fixed in the following way: We measured the centroid of the X-ray afterglow in the *Swift* frame of reference from the first 400 s of the XRT observations. Then the X-ray afterglow centroid was adjusted to match the position determined by Gehrels et al. (2005) and Burrows et al. (2005; who registered a 50 ks *Chandra* image to Two Micron All Sky Survey coordinates and then registered a 30 ks XRT image to the *Chandra* image). Hence, we apply a shift to the *Swift* reference frame of ΔR.A.(J2000.0) = −2″.57, Δdecl.(J2000.0) = −2″.16.

In order to characterize the intracluster emission, two point sources near the cluster were excluded and the source regions were filled with a Poissonian pixel value distribution sampled from the surroundings (using the `dmfilth` procedure in CIAO 3.2). Finally, we ran the `wavdetect` procedure on the resulting image for determining the centroid of the intracluster emission.

X-ray spectra were generated from events in the 0.5–7 keV range within a circular region centered on the cluster X-ray centroid and with a radius between 1′.75 and 2′.17 (corresponding to the radius at which the intracluster emission is 1.5 times above the background level or equals the background level, respectively). The energy bounds were chosen so as to leave out the lowest energies where the spectral calibration is most uncertain and to disregard the highest energies dominated by background. Background spectra were generated from circular regions devoid of sources, not overlapping with the cluster extraction region or each other, and with the same radius as used for the intracluster emission. The average background level is ∼10% of the intracluster emission. We used the Xspec package version 12.2.0 (Arnaud 1996) to fit background-subtracted spectra of the intracluster emission, binned to a minimum of 20 counts per bin, with a hot plasma model (MEKAL; Mewe et al. 1985; Liedahl et al. 1995) absorbed by neutral matter along the line of sight. The Galactic absorbing column density in this direction is $N_{\rm H} \sim 1.52 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990).

[8] See http://cxc.harvard.edu/ciao.

3. CLUSTER X-RAY PROPERTIES

The intracluster X-ray emission centroid is R.A.(J2000.0) = $12^{\rm h}36^{\rm m}19^{\rm s}.03$, decl.(J2000.0) = +28°59′13″ (with an uncertainty of ∼5″). This is 72″ offset from the center of the XRT error circle. The diffuse emission extends to about 2′, corresponding to 430 kpc for a cluster redshift of $z = 0.2248$ (Bloom et al. 2005); 327 net counts (0.3–10 keV) are detected within 2′.17 of the X-ray centroid. With the spatial resolution achieved by the photon statistics, the morphology of the intracluster emission is close to circular with a slight northeast-southwest elongation in the cluster outskirts (see Fig. 1). Observations obtained with the *Chandra X-Ray Observatory* can further reveal the structure of the intracluster medium (Patel et al. 2005). The near coincidence between the X-ray centroid and several bright elliptical galaxies strongly suggests that this is the bottom of the cluster potential well rather than the optical center of ZwCl 1234.0+2916 [R.A.(J2000.0) = $12^{\rm h}36^{\rm m}28^{\rm s}.0$, decl.(J2000.0) = +28°59′30″; Zwicky & Herzog 1963] or NSC J123610+285901 [R.A.(J2000.0) = $12^{\rm h}36^{\rm m}10^{\rm s}.2$, decl.(J2000.0) = +28°59′01″; Gal et al. 2003]. At the cataloged optical cluster centers, no enhancement in X-ray emission is seen.

The spectrum of the intracluster medium within a radius of 2′.17 of the X-ray centroid is well fitted ($\chi^2 = 15.8$ for 21 degrees of freedom) by a MEKAL model with absorption fixed at the Galactic value and a typical abundance of $Z = 0.25\ Z_\odot$ (Mushotzky & Loewenstein 1997; see Fig. 2). The best-fit temperature is $kT = 3.65^{+2.26}_{-1.22}$ keV, and the 0.5–2 keV flux is $1.21^{+0.33}_{-0.37} \times 10^{-13}$ ergs cm^{-2} s^{-1}. The main systematic error in determining the temperature and flux is the background subtraction. Using four different background regions results in best-fit temperatures between $kT = 3.01^{+1.84}_{-0.83}$ keV and $kT =$

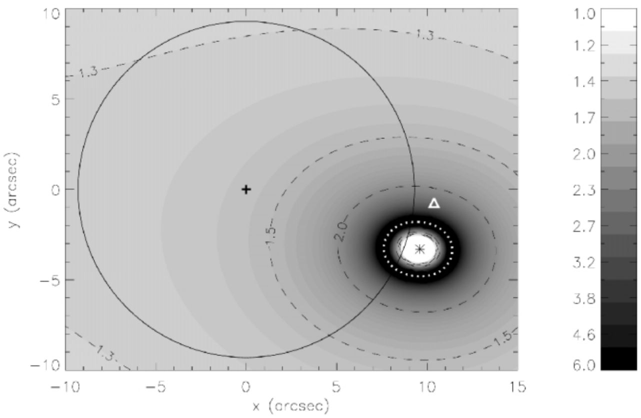

Fig. 3.—Gravitational lensing magnification in and around the XRT error circle (centered on the black plus sign) shown as a logarithmic gray scale (intensity scale on the right) and contours (*dashed lines*). North is up, and east is to the left. The source was placed at a redshift $z = 3$, and the mass distribution of the galaxy G1 and the cluster ZwCl 1234.0+02916 were modeled as isothermal ellipsoids with masses determined from the velocity dispersion and the X-ray temperature, respectively. The black asterisk is the center of the galaxy G1. The white triangle marks the location of the source revealed by subtracting a model of galaxy G1 (Hjorth et al. 2005), and the white, dotted line is a critical curve.

$3.78^{+2.71}_{-1.26}$ keV, and 0.5–2 keV fluxes between $0.96^{+0.52}_{-0.66} \times 10^{-13}$ and $1.34^{+0.50}_{-0.57} \times 10^{-13}$ ergs cm^{-2} s^{-1}.

We also investigated the influence on the best temperature from varying (1) the cluster emission extraction radius, (2) the absorbing column density, and (3) the intracluster abundance. Fitting the spectrum extracted within a radius of 1′.75 of the cluster X-ray centroid yields a temperature of $kT = 3.79^{+2.77}_{-1.21}$ keV. Letting the absorbing column density be a free parameter in the fit results in a best-fit value of $N_{\rm H} = 7.5^{+12.27}_{-7.5} \times 10^{20}$ cm^{-2}, and the best-fit temperature is $kT = 2.90^{+2.30}_{-1.00}$ keV. However, given that only a small amount of extragalactic absorption is expected (Allen et al. 2001), and that the Galactic absorbing column density is 50% uncertain in the worst case, a maximum column density of $N_{\rm H} = 2.28 \times 10^{20}$ cm^{-2} is expected. For this column density, the best-fit temperature is $kT = 3.54^{+2.32}_{-1.16}$ keV. The abundance is constrained to be $Z < 1.5\ Z_\odot$, and varying the abundance in the range 0.2–0.3 $Z_\odot$ (corresponding to the observed abundance variation in clusters; Mushotzky & Loewenstein 1997) changes the best-fit temperature by only ∼1%.

From the above analysis, we conclude that the global temperature of the ZwCl 1234.0+02916 intracluster medium is $kT = 3.65^{+2.26+0.15}_{-1.22-0.64}$ keV, where the latter uncertainty is due to systematics from background subtraction. Within the errors, this is consistent with the temperature derived by Bloom et al. (2005; $kT = 5.25^{+3.36}_{-1.68}$ keV). For a cluster redshift of $z = 0.2248$, the 0.1–2 keV luminosity is $(2.5 \pm 0.7) \times 10^{43}$ ergs s^{-1}, which is in good agreement with the expected luminosity from the empirical luminosity-temperature relation of clusters (Popesso et al. 2005). The X-ray properties of ZwCl 1234.0+02916 thus shows it to be a cluster intermediate to the Virgo and Coma clusters.

The cluster mass can be estimated from an empirical mass–X-ray temperature relation. Using the X-ray–determined mass-temperature relation of Arnaud et al. (2005) for their full sample, we find $M_{500} = 2.2^{+3.3}_{-0.6} \times 10^{14}\ M_\odot$, taking into account the uncertainties in the mass-temperature relation and the uncertainties in the temperature. The value M_{500} is the mass within the radius at which the mean cluster density is 500 times the critical density of the universe. From the optically determined mass-temperature relation of Popesso et al. (2005), we find $M_{500} = 2.3^{+3.1}_{-1.2} \times 10^{14}\ M_\odot$, in excellent agreement with the above mass estimate.

4. GRAVITATIONAL LENSING MAGNIFICATION

The alignment of the GRB 050509B XRT error circle and a bright elliptical galaxy, G1, in the cluster ZwCl 1234.0+02916 makes it relevant to consider the possibility that GRB 050509B is a gravitationally lensed background source (Engelbracht & Eisenstein 2005). Hence, we have calculated the gravitational lensing magnification from G1 and the cluster for several possible redshifts of GRB 050509B.

The gravitational lensing calculations were carried out using the `gravlens` software package (Keeton 2005). We model the galaxy as a singular isothermal ellipsoid with an axis ratio of 0.81 (Bloom et al. 2005) with the semimajor axis aligned along a position angle of 90°, a velocity dispersion of 260 ± 40 km s^{-1} (Bloom et al. 2005), and the cluster as a singular isothermal sphere with $M_{500} = 2.2^{+3.3}_{-0.6} \times 10^{14}\ M_\odot$ (see § 3). We take the center of the XRT error circle to be at R.A.(J2000.0) = $12^{\rm h}36^{\rm m}13^{\rm s}.58$, decl.(J2000.0) = +28°59′01″.3 (Gehrels et al. 2005) and choose that as the center of our coordinate system. We place the center of the galaxy G1 at R.A.(J2000.0) = $12^{\rm h}36^{\rm m}12^{\rm s}.86$, decl.(J2000.0) = +28°58′58″.0 and the center of the cluster at the X-ray centroid of the diffuse cluster emission (see § 3).

Below we give results for point sources at the expected lower and upper limit on the GRB 050509B redshift $z = 1.3$ and $z = 3$, respectively. Due to the blue continuum and lack of emission lines in the faint galaxies in the XRT error box, the lower limit on their redshift is $z \approx 1.3$ (Bloom et al. 2005). The upper limit on the redshift is motivated by models predicting an intrinsic duration of a gamma-ray burst longer than 8 ms (Lee et al. 2005). We note that choosing a larger upper limit does not affect our conclusions.

Taking uncertainties in the velocity dispersion of G1 into account, we find an Einstein radius for G1 of $b = 1.67^{+0.55}_{-0.47}$ arcsec for $z = 3$ and $b = 1.50^{+0.49}_{-0.42}$ arcsec for $z = 1.3$. Similarly, we get for the cluster (taking the uncertainty in the cluster mass into account) that $b = 9.7^{+8.2}_{-1.8}$ arcsec for $z = 3$ and $b = 9.0^{+7.6}_{-1.7}$ arcsec for $z = 1.3$. We then calculate the median magnification within the XRT error circle of radius 9″.3 (Gehrels et al. 2005; see Fig. 3). Most of the magnification is provided by the galaxy G1, and the main effect of the cluster is to increase the magnification in the east-west direction.

The XRT error circle crosses the critical curves (paths in the image plane where a point source will be exposed to infinite magnification) for nearly all mass models of G1 and the cluster. The median of the magnification within the error circle is a factor of $1.3^{+0.4}_{-0.1}$ for $z = 3$ and $1.3^{+0.3}_{-0.1}$ for $z = 1.3$. We thus find that the potential magnification of GRB 050509B is typically a factor of 1–2, fairly independent of the redshift of GRB 050509B. However, if GRB 050509B is positioned within ∼2″ of G1 it could be more strongly magnified. We note that the source revealed by subtracting away G1 (Hjorth et al. 2005), situated 2″.68 from the center of G1, is not a strongly lensed background source.

5. DISCUSSION

From our gravitational lensing study, we conclude that lensing is not strongly boosting the probability that GRB 050509B is situated in a background galaxy. Furthermore, Bloom et al.

(2005) estimate that the probability of a chance alignment between GRB 050509B and G1 is $\sim 5 \times 10^{-3}$ (using the apparent magnitude of G1), while Gehrels et al. (2005) arrive at a probability of $\sim 1 \times 10^{-4}$ (using the luminosity and distance of G1). Interestingly, a correlation between error boxes of short bursts in the BATSE catalog and the positions of galaxies in the local universe has been claimed (Tanvir et al. 2005).

We now proceed to estimate the probability of a chance alignment between the XRT error circle and a cluster of galaxies with an X-ray flux and optical richness at least as large as that of ZwCl 1234.0+02916. The sky surface density of clusters to a 0.5–2 keV flux limit of the ZwCl 1234.0+02916 flux is well determined to 0.5–1 clusters per square degree from several X-ray cluster surveys (Rosati et al. 1998). The probability for a chance alignment within 75″ of the cluster center and the GRB 050509B error circle center is equal to the sky coverage fraction of such clusters with a radius of 75″, i.e., $(0.7\text{–}1.3) \times 10^{-3}$. The sky surface density of clusters in the Northern Sky Optical Cluster Survey with a richness at least as large as NSC J123610+285901 ($N_{\rm gals} = 24.3$, corresponding to less than Abell richness class 0) is ~ 1.2 deg^{-2} (Gal et al. 2003), yielding a chance alignment probability of $\sim 1.6 \times 10^{-3}$. Although a posteriori statistics is always uncertain, GRB 050509B comprises the first strong case for a short burst located in a galaxy cluster, based on either the X-ray flux or the optical richness of ZwCl 1234.0+02916. The association of GRB 050509B with ZwCl 1234.0+02916 provides independent evidence that GRB 050509B is also associated with the galaxy G1 since this is a cluster member. Interestingly, it has recently been suggested that the line of sight toward the short burst GRB 050813 coincides with a cluster at redshift $z = 0.72$ (Gladders et al. 2005; Berger 2005). Previously, studies of the few small error boxes of short bursts have not revealed any short burst associated with a cluster (Hurley et al. 2002; Nakar et al. 2005).

A statistical correlation between gamma-ray burst error boxes (of short as well as long bursts) and the position of Abell clusters has been claimed (Kolatt & Piran 1996; Struble & Rood 1997), but subsequent refined analyses have failed to confirm this (Gorosabel & Castro-Tirado 1997; Hurley et al. 1999). However, Abell clusters are relatively nearby and rich, so a correlation between short bursts and Abell clusters is only expected if short bursts occur predominantly within the completeness redshift of Abell clusters ($z \lesssim 0.15$; Ebeling et al. 1996). The likely association between GRB 050509B and the cluster ZwCl 1234.0+02916 motivates further studies of the spatial correlation between galaxy clusters and short-burst sky positions. Since ZwCl 1234.0+02916 is less rich than Abell clusters, it would be beneficial to use cluster catalogs including poorer and more distant clusters. Such studies would provide interesting constraints on the environments of short bursts and hence on their origin.

If, as suggested by the favored models (Piran 2005), short bursts originate from merging of compact stellar remnants, their progenitors are 10^6–10^9 yr old (Voss & Tauris 2003). Targeting the environment of short bursts is thus potentially a new independent way for tracing the old stellar population throughout the universe. Up to now, entire populations of old stars in galaxies have been identified through their integrated optical/near-infrared colors. Short bursts are promising pointers to sites of individual old stars, revealing the spatial distribution of old stars, be they located in cluster ellipticals, field galaxies, or even in intergalactic space (Fukugita et al. 1998).

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Facilities: VLT: Antu (FORS2), Swift(XRT)

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